How to Change Factual Beliefs Using Laws and Dependence Information

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Abstract. We investigate how belief change operations can be effectively constructed. To that end we suppose given a set of laws (alias integrity constraints) together with a relation of dependence between formulas.

1 Introduction

When changing a set of beliefs K by some new piece of information (input) A, we must adjust the beliefs of K in a way such that A is believed. The result of such a belief change operation is a new set of beliefs $K \star A$.

The central question in the theory of belief change is what is meant by a minimal change of a state of belief. E.g. the well-known AGM rationality postulates for belief revision (AGM85, Gär88) partially answer that question. Another answer are the update postulates of (KM92). They all give requirements for the interplay between the (metalinguistic) belief change operator on the one hand and the classical connectives $\wedge$, $\vee$, $\neg$ and the notions of consistency and theoremhood on the other.

As pointed out in (Gär90), "the criteria of minimality that have been used [in the models for belief change] have been based on almost exclusively logical considerations. However, there are a number of non-logical factors that should be important when characterizing a process of belief revision." Gärdenfors focusses on the notion of dependence (he uses the synonymous term 'relevance'), and proposes the following preservation criterion:

If a belief state is revised by a sentence A,
then all sentences in K that are independent of the validity of A
should be retained in the revised state of belief.

This seems to be a very natural requirement for belief revision operations. But as Gärdenfors notes, "a criterion of this kind cannot be given a technical formulation in a model based on belief sets built up from sentences in a simple propositional language because the notion of relevance is not available in such a language."

Our aim is to put the notion of dependence in a formal framework, and to apply it to belief change. Such a notion should allow us to find algorithms for the effective construction of belief change operations in practical applications such as databases or robotics.

We view dependence as a weak causal connection between formulas: Given two formulas A and C, if C depends on A then changes concerning the truth value of A *might* (but need not) change the truth value of C. On the other hand, if C is independent of A then changes concerning the truth value of A will *never* influence the truth value of C. E.g. let p mean "it rains", and q "the grass is wet". Then q depends on p in the sense that there is a set of beliefs (e.g. $\{\neg q\}$) such that its revision by p makes the truth value of q change. On the other hand, if q means "the traffic light is red", then q is independent of p: Learning something about the weather (whether it started or stopped to rain) should not modify my beliefs concerning the colour of the traffic light. [1] On the other hand, if q means "the traffic light is red", then q is independent of p: Learning something about the weather (whether it started or stopped to rain) should not modify my beliefs concerning the colour of the traffic light.

As argued by Gärdenfors, dependence information enables us to construct revision operations: If we revise a set of beliefs K by some new piece of information A, then the resulting set $K \star A$ will at least contain all the formulas of K that are independent of A. (The same can be stated for updates *à la* Katsuno-Mendelzon.)

Another (and somewhat more popular) thing to integrate in a practical account of belief change are laws. Under the name integrity constraints, such priviledged formulas have been studied since a long time ago in databases and in knowledge representation. Laws are 'eternal' in the sense that they 'survive' every change of beliefs.

In this paper, we show how belief change operations based on a set of laws and a dependence relation can be effectively constructed. We suppose that a set of beliefs is represented by some finite set that is called a belief base. Nevertheless, we want to be syntax-insensitive: We want logically equivalent belief bases to be changed in the same way, and we want new pieces of information that are logically equivalent to lead to equivalent new belief bases. This will be achieved by the elimination of "inessential" atoms from formulas, via the use of prime implicates.

First we give the relevant definitions and stress the hypotheses we make. Then we introduce belief revision systems based on laws and dependence. Finally we present a reformulation and extension of the AGM-postulates that takes care of laws and dependences, and give the properties of our belief revision systems w.r.t. the latter.

2 Belief bases and syntax-sensitivity

If we want to store beliefs on a computer, we cannot represent them by deductively closed sets as done in the AGM framework, because such sets are infinite.

[1] Note that this may not be the case for other belief sets such as $\{q\}$.

What we need are finite *belief bases.*

Then a new problem shows up: For syntactically different but logically equivalent belief bases K_1 and K_2 it might be the case that some change operation modifies them differently. In other words, we might be sensitive to the syntax of the belief base.

This has been the starting point for the defense and study of syntax-sensitive belief change operations (Fuh91, Neb92, Han92). Despite its intuitive appeal, we think that the drawbacks of these approaches are too important: Take e.g. the four belief bases $\{p, q\}$, $\{p \wedge q\}$, $\{q \wedge p\}$, and $\{p \wedge p \wedge q\}$. Only very particular readings allow us to say that these bases do not represent the same state of affairs. Nevertheless, syntax-sensitive approaches admit operations which change these bases in four different ways.

It is for that reason we want to be syntax-insensitive. Precisely, syntax-insensitivity means two things: First, equivalent belief bases should be changed in the same way. Second, the syntactical form of the new piece of information should be irrelevant. In other words, change by logically equivalent formulas should lead to the same result. To ensure this we shall require the belief bases and the inputs to be of a particular form.

3 Classical logic

We work with the language of classical propositional logic with the connectives $\neg, \wedge, \vee, \top, \bot$. The set of atoms is denoted by *ATM*, and the set of formulas by FOR. For atoms we use $p, q, r \ldots$, and for formulas $A, B, C, \ldots$. For a given formula A, $atm(A)$ is the set of atoms having an occurrence in A. As usual, a *literal* is an atom or the negation of an atom, and a clause is a disjunction of literals. We do not distinguish between a clause and a finite set of literals. (Hence $\bot$ is the empty clause, and $\top$ is the empty set of clauses.) A finite set of formulas is called a *belief base.*

Given a set of formulas S, a formula A is said to be *S-consistent* iff $S \cup \{A\}$ is consistent.

Interpretations are subsets of *ATM*. Given a set of formulas S, an interpretation I is an *S-interpretation* iff $I \models A$ for all $A \in S$.

4 Normal forms and pure formulas

One way to get syntax-insensitive is to put formulas in some normal form. In particular, similar to (Sch93) we must avoid formulas containing atoms that can be eliminated by equivalence transformations.

Definition 1. A formula A is *pure* iff there is no equivalent formula containing less atoms.

E.g. $p \wedge q$ is pure, and $p \wedge (p \vee q)$ is not (because there exists an equivalent formula (viz. p) wherein q does not occur).

In terms of models, A is pure if and only if there is no atom p occuring in A such that for some classical p-interpretation $I \subseteq ATM$ we have $I \models A$ iff $I - \{p\} \models A$.

In classical logic, for every formula there exists an equivalent pure formula. (It is crucial here that $\top$ and $\bot$ are among our connectives, else there would be no pure formula equivalent to $p \vee \neg p$.) But how can we construct such pure formula? We need the notion of a prime implicate (Mar95).

Definition 2. A *prime implicate* of a formula A is a clause C such that

- $A \vdash C$, and
- for all clauses C' such that $A \vdash C'$ and $C \subseteq C'$ we have $C' \subseteq C$.

E.g. the clause $\{p\}$ is a prime implicate of $((p \vee q) \wedge p) \wedge (q \vee r)$, and $\{p, q\}$ is not.

We shall denote the set of all prime implicates of A by $A\!\downarrow$. E.g. $((p \vee q) \wedge p) \wedge (q \vee r)\!\downarrow = \{\{p\}, \{q, r\}\}$, and $(p \vee q) \wedge (\neg q \vee r)\!\downarrow = \{\{p, q\}, \{\neg q, r\}, \{p, r\}\}$.

Proposition 3. *The set of prime implicates of a formula is finite.*
The conjunction of the prime implicates of a formula A is equivalent to A.

Note that it is important for finiteness that we identify clauses such as $p \vee q$, $q \vee p$ and $p \vee p \vee q$, ... with the set $\{p, q\}$.

This gives us the normal form we need:

Proposition 4. *If $\vdash A_1 \leftrightarrow A_2$ then $A_1\!\downarrow = A_2\!\downarrow$.*

Moreover we have:

Proposition 5. *The conjunction of the prime implicates of a formula is pure.*

Hence we have now at our disposal a normal form into which belief bases and inputs can be transformed in order to warrant syntax-insensitivity.

5 Dependence relations

Definition 6. An *atomic dependence relation* $\leadsto_0$ is a binary relation on ATM that is reflexive.

(Note that we neither suppose symmetry nor transitivity.)

$\leadsto_0$ induces a dependence relation $\leadsto$ on the set of formulas FOR by

$$A \leadsto C \text{ iff there exist } p \in atm(A), q \in atm(C) \text{ such that } p \leadsto_0 q.$$

Hence our dependence relations have the following properties: [2]

- $A \not\leadsto \top$, $A \not\leadsto \bot$, $\top \not\leadsto A$, $\bot \not\leadsto A$,

[2] Although we do not have symmetry, this could be added without harm.

– If $A \rightsquigarrow C$ then $A \rightsquigarrow \neg C$ and $\neg A \rightsquigarrow C$.
– If $A \rightsquigarrow C$ then $A \rightsquigarrow C \triangle C'$ and $A \triangle A' \rightsquigarrow C$ for $\triangle = \wedge, \vee, \rightarrow, \leftrightarrow$.

The complement of a dependence relation $\rightsquigarrow$ is called an *independence relation* and is noted $\not\rightsquigarrow$.

Given a dependence relation, we can define the *orthogonal* $K \perp A$ of a belief base K w.r.t. a formula A, which is the set of those elements of K that are independent of A.

Definition 7. $K \perp A = \{C : C \in K \text{ and } A \not\rightsquigarrow C\}$.

E.g. let $\rightsquigarrow$ be constructed from

$$\rightsquigarrow_0 = \{(p,p), (q,q), (r,r), (t,t), (p,q)\}$$

Then $\{p, p \vee t, r \vee t\} \perp \neg p = \{r \vee t\}$.

We have supposed that the dependence relation is induced by the atomic dependence relation. Thus we have a dependence relation with very strong properties.

This is a compromise in order to economically represent beliefs. We are aware that there is no complete theoretical justification for that: There is no theory of uncertainty whose dependence relation has such properties as ours (Fin73, Coh94, FdCH95, DFdCHP94). Indeed, it might be the case that our way of representing things is too crisp: For three atoms p, q, r it might be the case that $p \not\rightsquigarrow r$ and $q \not\rightsquigarrow r$, but nevertheless $p \wedge q \rightsquigarrow r$. [3]

Note that the notion of dependence is rather fuzzy, and hence it is unclear what the natural and intuitive properties of a dependence relation are. E.g. if one adopts probability-based dependence, dependence becomes transparent with respect to negation (in the sense that A and C are dependent iff A and $\neg C$ are dependent), but not with respect to conjunction or disjunction. (Note that this has been criticized e.g. in (Gär78) and in (Gär90)). On the contrary, things are just the other way round in the case of possibility-based dependence (DFdCHP94).

The strong properties of our dependence relation may thus make us lose some complex formulas when it comes to the construction of the new set of beliefs. But on the other hand, it gives us a particularly economic knowledge representation: If we suppose the set of atoms ATM to be finite, both the atomic dependence relation $\rightsquigarrow_0$ and the atomic independence relation $\not\rightsquigarrow_0$ contain at most $card(ATM)^2$ elements.

Note that the strong properties of dependence relations with respect to negation, conjunction and disjunction make that we are syntax-sensitive in the sense that equivalent formulas may not have the same dependencies. E.g. $p \wedge (p \vee q)$ depends on p and q, but q is inessential. It will be the use of pure formulas that will make us syntax-insensitive here.

[3] An intuitive example mentioned to us by D. Dubois is obtained by reading p as "I take a bath", q as "I use a hairdryer", and r as "I am going to die".

Our notion of dependence is close to that of *topics* (alias themes) as studied in (FdCL91, Lug96, DJ94). There, the themes of a formula are what the formula is about. Then one can define two formulas to be dependent if they have some theme in common. (Such a dependence is called conversational in (Coh94). The only difference is that such a notion is always symmetric (which is a property we could add as well).

We make the hypothesis of *inertia* (San93): Even factual change does not occur massively, and "almost all" of the factual beliefs survive the change. Therefore, we can expect the atomic dependence relation to be much smaller than the independence relation. This is why we chose to represent the dependence relation instead of its complement.

6 Laws and factual change

Laws (alias integrity constraints) are viewed as being "eternal" and cannot be put into question. We suppose that a law is preserved under any change. Syntactically, a law is just an arbitrary formula of FOR. We note IC the set of laws of a given domain, and we shall suppose that IC is consistent.

Hence the type of belief change that is in the scope of our approach does not allow the revision of laws. Our 'small changes' (Seg86) only concern contingent facts. We call them therefore *factual.* (As well, we shall suppose here that the dependence relation cannot be modified.)

Such a hypothesis being unsatisfactory for philosophers [4], we nevertheless think that it is reasonable and useful in the context of practical reasoning: change appears to be factual e.g. in databases or robotics.

7 Compatibility of laws and dependences

It is clear that laws and dependences are related. E.g. whenever $p \leftrightarrow q$ is in the set of laws we must have $p \leadsto q$ and $q \leadsto p$. The same holds for the law $p \to q$ (except if $IC \vdash \neg p \wedge q$). Such compatibilities or incompatibilities cannot be derived from the definition of dependence relations of section 5, where we did not say anything about laws yet.

A first naive requirement would be that whenever two atoms p and q both occur in some law, then they should be dependent. But this is clearly too strong. Take e.g. an electric circuit where some light is on exactly when two switches are closed (Lif86). Formally, this corresponds to a law $(p_1 \wedge p_2) \leftrightarrow q$, where p_i is read 'switch i is up', and q 'the light is on'. If I am told that the first of the two switches has been moved, I am prepared to change my beliefs concerning the light, but not those concerning the position of the second switch. Formally, $p_1 \leadsto q$, $p_2 \leadsto q$, but $p_1 \not\leadsto p_2$.

[4] Note that the evolution of laws was the motivation of the founders of the AGM-theory: Alchourrón and Makinson were interested in the derogation of (legal) norms, and Gärdenfors in the evolution of scientific theories.

Intuitively, the dependence relation must contain enough dependences of p in order to allow any change of p respecting the laws. The following condition is central and warrants what we need.

Definition 8. A set of laws IC and an atomic dependence relation $\rightsquigarrow_0$ are *compatible* iff for every IC-interpretation I and every IC-consistent atom p there exists an $(IC \wedge p)$-interpretation I^+ and there exists an $(IC \wedge \neg p)$-interpretation I^- such that all atoms in $(I - I^+) \cup (I - I^-)$ depend on p. [5]

E.g. let $IC = \{p \rightarrow q\}$. If $p \not\rightsquigarrow_0 q$ or $q \not\rightsquigarrow_0 p$ then IC and $\rightsquigarrow$ are incompatible. Contrarily, if $\rightsquigarrow$ is constructed from $\rightsquigarrow_0 = \{(p,p),(q,q),(p,q),(q,p)\}$ then IC and $\rightsquigarrow$ are compatible.

This gives us the following property for general formulas.

Proposition 9. *Let IC a set of laws and $\rightsquigarrow$ a dependence relation such that IC and $\rightsquigarrow$ are compatible. Let A be an IC-consistent formula. Then for every IC-interpretation I there is an $(IC \wedge A)$-interpretation I' such that all atoms in $I - I'$ depend on A.*

Suppose the language is finite, and $\rightsquigarrow$ and IC are given. It is straightforward to check compatibility of $\rightsquigarrow$ and IC: we must instantiate A by all maximally consistent conjunctions of literals. Such compatibility checks are exponential, but note that they can be done once for ever when a particular system for reasoning about actions and plans is designed. Now a way to generate all minimally compatible dependence relations is to incrementally apply compatibility tests.

8 Dependence-based belief change

Now we are ready to formally define dependence-based belief change operations.

Definition 10. A belief change system is a couple $(IC, \rightsquigarrow_0)$, such that

- IC is a finite set of formulas (the laws),
- $\rightsquigarrow_0$ is a dependence relation, and
- IC and $\rightsquigarrow_0$ are compatible.

Now for every belief change system we can construct a unique revision operation $\star$.

Definition 11. Let $(IC, \rightsquigarrow_0)$ be a belief change system. The associated revision operation $\star$ is such that for every belief base K

- $K \star A = A{\downarrow} \cup IC$ if $\emptyset \in K{\downarrow}$
- $K \star A = K \cup \{A\} \cup\ IC$ if $K \cup\ IC \not\vdash \neg A$
- $K \star A = ((K{\downarrow}) \bot (A{\downarrow})) \cup A{\downarrow} \cup IC$ if $K \cup\ IC \vdash \neg A$ and $\emptyset \notin K{\downarrow}$.

[5] i.e. $p \rightsquigarrow_0 q$ for all atoms $q \in I - I^+$, and $p \rightsquigarrow_0 q$ for all atoms $q \in I - I^-$, and

In other words, in order to revise a belief base K by A we first check whether K is IC-inconsistent. If this is the case then $K \star A$ is $A{\downarrow} \cup IC$. Else we check whether K and A are IC-consistent. If this is the case, we simply add A and IC to K. Else we put K and A in normal form by computing the respective sets of prime implicates $K{\downarrow}$ and $A{\downarrow}$, and then compute the orthogonal $(K{\downarrow})\bot(A{\downarrow})$. The new belief base results from adding $A{\downarrow}$ and IC to the latter.

E.g. let $IC = \emptyset$, and let $\leadsto$ be constructed from

$$\leadsto_0 = \{(p,p),(q,q),(r,r),(t,t),(p,r)\}$$

Let $K = \{p, q \vee t, r \vee t\}$. Then $K \star \neg p = \{q \vee t, \neg p\}$.

Clearly, computing prime implicates is expensive. But it seems to be the only way to avoid syntax-sensitivity.

9 Postulates

In the AGM-framework (Gär88), nothing is said about laws. Therefore, some postulates must be reformulated in terms of IC-consistence in order to take them into account. We have adapted the formulation in (KM92). Only the postulate R0 does not appear in the original set.

R0$_{IC}$ $K \star A$ is a belief base such that $K \star A \vdash IC$.
R1$_{IC}$ $K \star A \vdash A$.
R2$_{IC}$ If $K \cup \{A\}$ is IC-consistent then $K \star A \vdash K$.
R3$_{IC}$ If A is IC-consistent then $K \star A$ is IC-consistent.
R4$_{IC}$ If $K_1 \dashv\vdash K_2$ and $A_1 \dashv\vdash A_2$ then $K_1 \star A_1 \dashv\vdash K_2 \star A_2$. [6]
R5$_{IC}$ $(K \star A_1) \cup \{A_2\} \vdash K \star (A_1 \wedge A_2)$.
R6$_{IC}$ If $(K \star A_1) \cup \{A_2\}$ is IC-consistent then $K \star (A_1 \wedge A_2) \vdash (K \star A_1) \wedge A_2$.

(Remember that we do not distinguish between a finite set and the conjunction of its elements.)

But we not only have things to say about laws, but also about dependences. The first and main postulate involving dependence that we can formulate is

R1$_{\leadsto}$ If $A \not\leadsto C$ and $K \vdash C$ then $K \star A \vdash C$.

This is just the preservation criterion of (Gär92).

But we can also say more subtle things about the interplay between dependence and the classical connectives. We only give the following two postulates. The first one deals with conjunction.

R2$_{\leadsto}$ If $A_1 \not\leadsto A_2$ then $K \star (A_1 \wedge A_2) \vdash (K \star A_1) \star A_2$.

This means that revision by the conjunction of independent formulas can be done sequentially.

The next postulate is about disjunction.

[6] $A \dashv\vdash B$ is a shorthand for '$A \vdash B$ and $B \vdash A$'.

R3$_{\leadsto}$ If $A_1 \not\leadsto A_2$, $A_2 \not\leadsto A_1$ and $K \vdash \neg(A_1 \vee A_2)$ then $K \star (A_1 \vee A_2) \vdash \neg(A_1 \wedge A_2)$.

In other words, if both $\neg A_1$ and $\neg A_2$ are in the belief set and A_1 and A_2 are independent of each other, then the revision by $A_1 \vee A_2$ leads to the exclusive disjunction.

To illustrate that, suppose a murder has occurred, and the butler and the gardener (who were both initially supposed to be innocent) get suspected: Either the butler was it, or the gardener, *or both*. Suppose my opinion about the butler's guiltiness does not depend on that about the gardener, and vice versa. Then R3$_{\leadsto}$ says that we should suppose that exactly one of them is the murderer (i.e. we suppose they did not act together). Under the independence hypothesis this fits nicely in Gärdenfors' principle of informational economy. In turn, if this hypothesis cannot be made, it is somewhat adventurous to exclude the possibility of both being murderers.

Note that such a principle of minimal change (together with the underlying independence hypothesis) is implicit in several formal approaches to the dynamics of belief such as circumscription (EGG93) or Winslett's Possible Models Approach (Win88).

10 Properties

Proposition 12. *Every dependence-based belief change operations satisfies the AGM revision postulates R0$_{IC}$ - R5$_{IC}$.*

It is easy to prove that our belief change operation satisfies R0$_{IC}$, R1$_{IC}$, R2$_{IC}$, and R5$_{IC}$. In order to establish that equivalent formulas give us the same result (R4$_{IC}$) we use the properties of prime implicates (proposition 4). It is more difficult to establish that the result of a revision by IC-consistent formulas is IC-consistent (R3$_{IC}$). Here we must exploit that formulas and belief sets correspond to prime implicates, and that dependences and constraints are compatible: For the main case, suppose K and A are consistent. Hence there is a classical model I of K. As $K \leftrightarrow K\!\downarrow$ and $(K\!\downarrow)\bot(A\!\downarrow) \subseteq K\!\downarrow$, I is a model of $(K\!\downarrow)\bot(A\!\downarrow)$ as well. As IC and $\leadsto$ are compatible, by proposition 9 there exists a classical $IC \wedge A$-interpretation I' such that all atoms in $I - I'$ depend on A. As $(K\!\downarrow)\bot(A\!\downarrow)$ does not contain any of these atoms, I' is a $(K\!\downarrow)\bot(A\!\downarrow)$-interpretation as well. Hence $((K\!\downarrow)\bot(A\!\downarrow)) \cup A\!\downarrow \cup\, IC$ is satisfiable.

Proposition 13. *There are dependence-based belief change operations which do not satisfy the postulate R6$_{IC}$.*

In the proof we give IC and $\leadsto_0$ such that the associated revision operation does not satisfy R6$_{IC}$.

Note that R6$_{IC}$ has been criticized by means of a counterexample (Sta92).

Proposition 14. *Every dependence-based belief change operations satisfies the postulates R1$_{\leadsto}$, R2$_{\leadsto}$, and R3$_{\leadsto}$.*

11 Conclusion

We have showed how one can construct a belief change operation from a set of laws together with a dependence relation. We have shown that all AGM-postulates except one are satisfied, and we have stated several new dependence-based postulates. It would be nice to find a set of postulates completely characterizing our family of operations.

One can proceed in the same way in the case of updates *à la* Katsuno-Mendelzon (KM92). There, given a set of laws IC and an atomic dependence relation $\leadsto_0$ the definition of the update operation $\leftarrow\!\diamond$ is even simpler:

– $K \leftarrow\!\diamond A = ((K\!\downarrow) \bot (A\!\downarrow)) \cup A\!\downarrow \cup\ IC$

Then the only KM-postulate which does not immediately follow is

(U8) $(B_1 \vee B_2) \leftarrow\!\diamond A \ \leftrightarrow .\ B_1 \leftarrow\!\diamond A \vee B_2 \leftarrow\!\diamond A$

This must be investigated further.

Finally, another continuation of this paper is to look for other natural postulates for revisions involving dependence.

12 Acknowledgements

Some of the ideas in this paper have been presented at the workshop on formal epistemology that has been organized by Hans Rott at the European Summer School on Logic, Language and Information in Barcelona (August 1995).

Thanks to Daniel Lehmann for several email exchanges on the interpretation of disjunction in revision. I am indebted to Pierre Marquis for discussions on prime implicates, and to Luis Fariñas del Cerro and Marcos A. Castilho for stimulating comments on preceding drafts.

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